Collision of the Mocha fracture zone and a <4 Ma old wave of orogenic uplift in the Andes (36°–38°S)

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ABSTRACT

The southern Central and northern Patagonian Andes (34°–45°S) are characterized by low to no crustal seismicity at the retroarc fold and thrust belt, in contrast to the Pampean flat subduction zone located immediately to the north (27°–33°30′S). Detailed examination of this area shows no indication of contractional neotectonics with the exception of the segment located between 36° and 38°S. There, out-of-sequence transpressional deformation, initially developed in the 1.7–1.4 Ma interval, affects the western retroarc between 36° and 38°S next to the arc zone. It is between these latitudes that contractional deformation <3.6 Ma old developed in the forearc region. Oblique collision of the Mocha fracture zone and its associated rise explains the distribution, extent, and timing of <3.6 Ma contractional deformations from the forearc to the foreland, as well as incipient shallowing of the Nazca plate beneath the South American plate, which has been inferred from seismic, gravimetric, and arc dynamics studies.

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INTRODUCTION

As a general paradigm it is broadly accepted that the Andes are formed by the subduction of a series of oceanic plates beneath the South American plate. The southern Central and northern Patagonian Andes are formed in an area of collision of the Nazca and South American plates. The Nazca plate is at present formed at the Chilean mid-ocean ridge, segmented by a series of NE transform faults that at the site of subduction produces strong gradients in oceanic floor age (Fig. 1). These transform faults are associated with important bathymetric anomalies that have been described recently as isostatically anomalous buoyant settings produced by highly serpentinized crust (Contreras Reyes, 2008). The South American margin between 38° and 40°S is the locus of subduction of a plateau <4000 m below sea level, herein named the Mocha rise, which is crossed at its mid sector by the Mocha fracture zone (Fig. 1). The Andean retroarc between 34° and 45°S, compared to the Andes north of 33°30′S, is characterized by scarce intracrustal seismicity. Most of the retroarc fold and thrust belt at these latitudes lacks shallow seismicity as well as neotectonic indicators of contractional activity <3 Ma, being restricted to both the arc zone next to the Argentinian-Chilean boundary and the coastal zone (Bohm et al., 2002) (Fig. 2). In the arc zone over the eastern Andean slope the Antiñir-Copahue fault system is an active thrust system developed between 36° and 38°S (Folguera et al., 2004) (Fig. 3), affecting the Cretaceous to Miocene fold and thrust belt in the hinterland area (Folguera et al., 2006). Subcrustal seismicity occurs mainly in the Wadatti-Benioff zone at these latitudes (Bohm et al., 2002), indicating a roughly 30° east-dipping zone beneath the South American plate. However, two independent lines of evidence have refined this picture in the past few years, showing some additional complexity. On the one hand, three seismic refraction profiles crossing the forearc and arc zones have shown that the subduction angle at 37°S is dipping up to 6.5° shallower than to the north and south of this latitude (Krawczyk et al., 2006). In addition, this observation is compatible with a long-wavelength gravity anomaly of up to 80 mGal observed between 36° and 38°S that characterizes the coastal zone (Fig. 2). This anomaly has been modeled after a shallower geometry of the subducted oceanic (Nazca) plate beneath the South American plate (Tašárová, 2004; Hackney et al., 2006), as shown in the seismic surveys. This "shallowing" of the subducted Nazca plate beneath the South American plate could be a transient feature as inferred from arc dynamics in the past 3–4 Ma. Early Pliocene arc-related associations (Vergara and Muñoz, 1982) have been mapped extensively in this Andean segment. South of 38°15′S, their westernmost extent coincides spatially with the location of 2 Ma younger modern volcanoes associated with the arc front (Stern, 2004), while to the north they are systematically displaced, with the youngest arc chain 40–50 km east of the early Pliocene arc (Fig. 2). This implies an eastward redefinition of the asthenospheric wedge, the site of arc-related magma production during the past 3–4 Ma, coincident with the shallower subducted Nazca plate zone inferred from seismic and gravimetric studies. This paper explores the relationship of a colliding fracture zone with flat slab subduction and its deformational and magmatic effects on the overriding plate. Even though the influence of subducted aseismic ridges on the determination of shallow subduction zones (Nur and Ben-Avraham, 1981; Pilger, 1981; Gutscher et al., 2000; among others) had been discussed, no such relation had been proposed for the case of subduction of serpentinized, thus highly buoyant, transform fracture zones. Therefore, a new tectonic model is provided for the 36°–38°S Andean segment, explaining <4 Ma old arc dynamics and orogenic construction. Detailed connections between deformation of the overriding plate and a flattened slab have not been described in many places. The Andean subduction zone between 36° and 38°S has the potential to provide a better understanding of the kinematic and dynamic connection between shallow subduction and deformation of the overriding plate globally, which is the main thrust of this contribution.

LESS THAN 4 Ma OLD DEFORMATIONS IN THE ANDES BETWEEN 36° AND 40°S

Less than 4 Ma old deformations in the Main Andes between 36° and 40°S are governed by

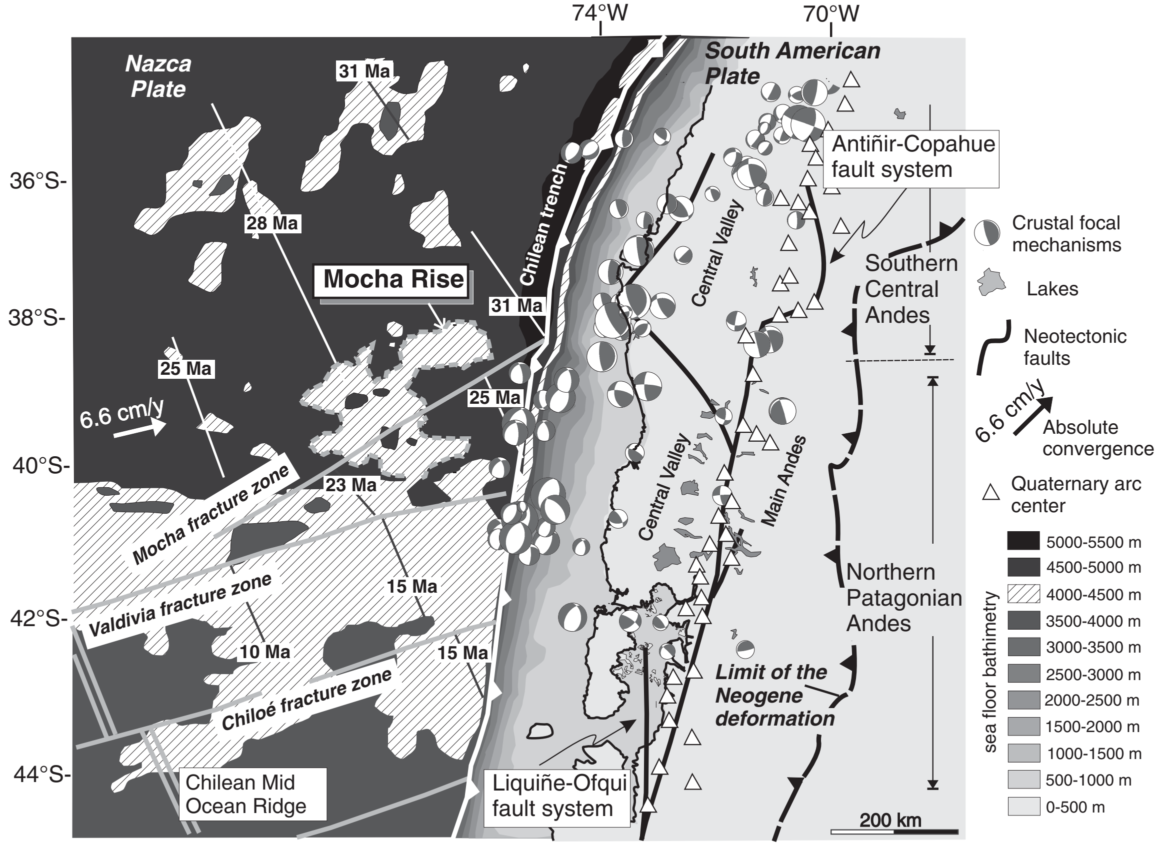

Figure 1. Southern Central and northern Patagonian Andes formed by the subduction of the Nazca plate beneath the South American plate. Note the highly variable bathymetry at the Chilean trench and the high seismicity at the point where the Mocha fracture zone meets the trench. Numbers in segments parallel to the Chilean mid-ocean ridge indicate the age of the ocean floor in millions of years. Seismicity has been taken from Harvard CMT catalog (http://www.globalcmt.org/CMTsearch.html).

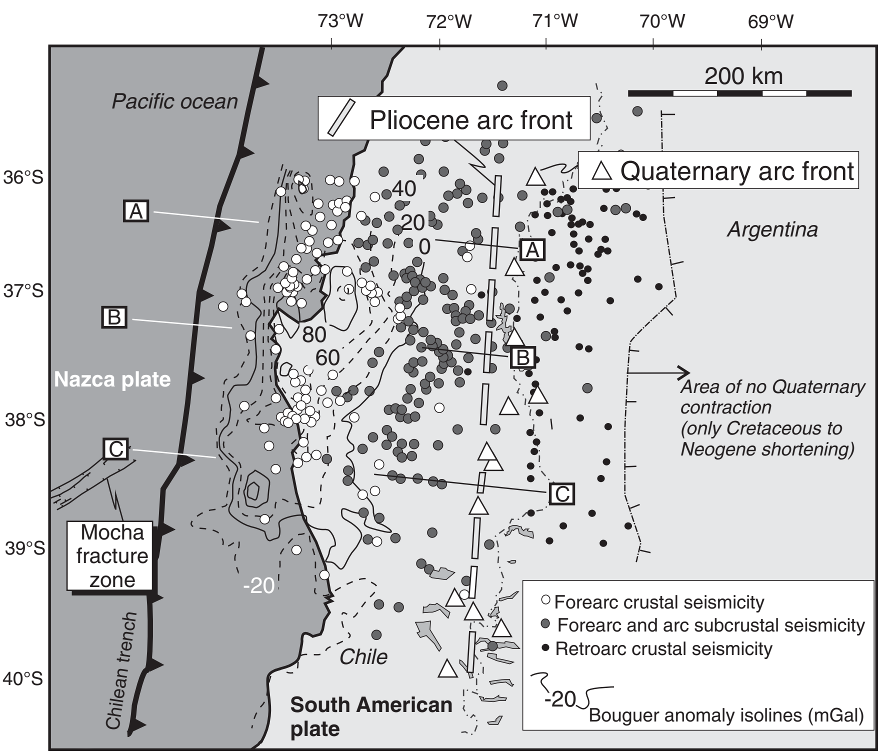

Figure 2. Subduction of the Nazca plate beneath the South American plate at 35°–40°S and associated seismicity and gravity. A, B, and C indicate positions of seismic refraction profiles (Krawczyk et al., 2006) at the forearc zone, which indicate a 6°–7° shallower subduction angle at B with respect to neighboring surveys. Onshore positive and long wavelength gravity anomalies between 36° and 38°S have been ascribed to the effect of the oceanic Nazca plate at depth: 3D density models (Tašárová, 2004; Hackney et al., 2006) corroborate a shallower subduction angle at B. Note that Pliocene and Quaternary arc fronts, coincident south of 38°15′S, are separated for 40–50 km north of this latitude in coincidence with the inferred segment of shallower forearc subduction.

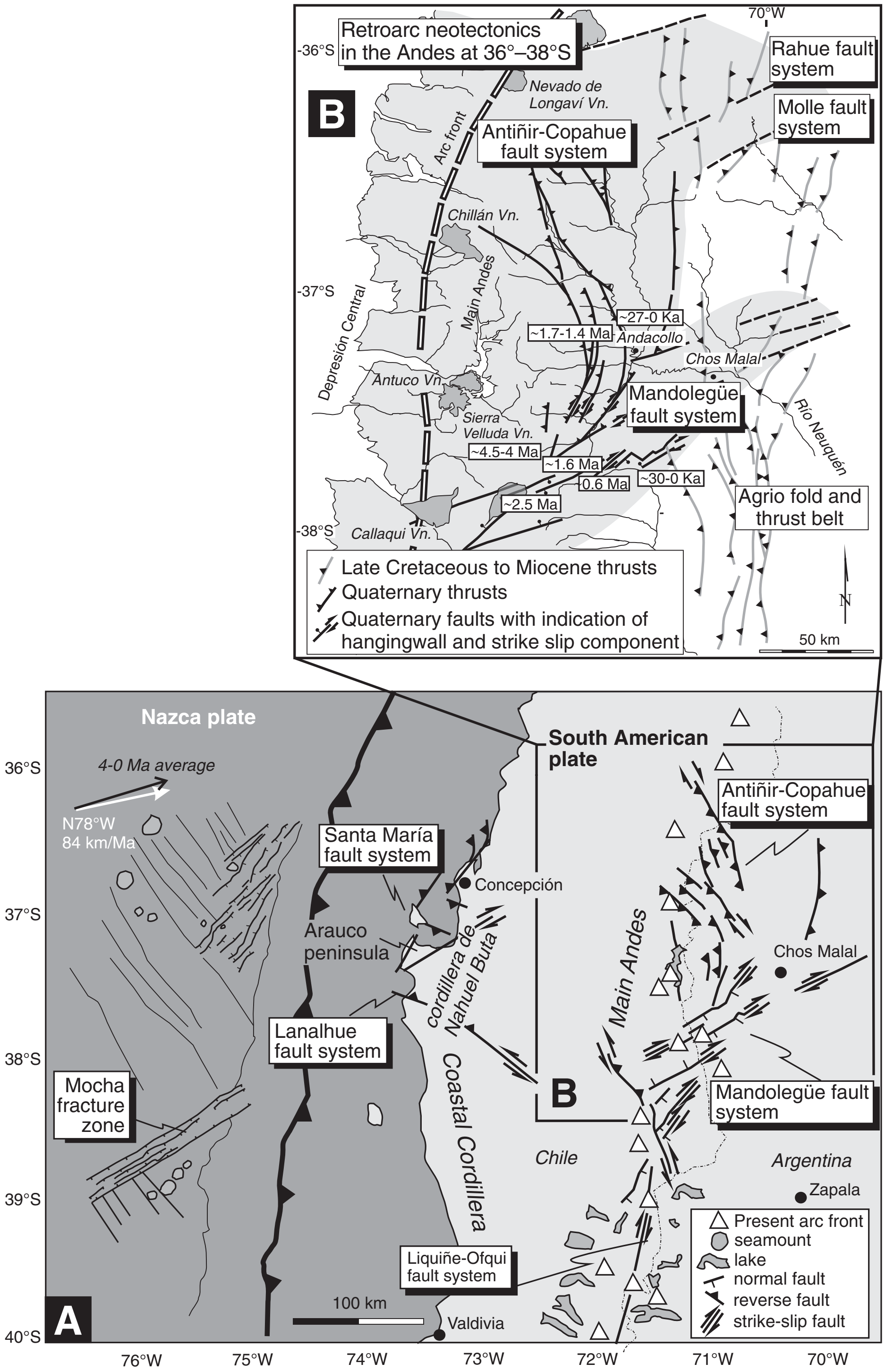

Figure 3. (A) Less than 3.6 Ma old deformation through the Andean arc and forearc between 36° and 40°S (from Folguera et al., 2004, 2006; Melnick et al., 2006; Rosenau et al., 2006). The average relative convergence between the Nazca and South American plates in the past 4 Ma is from Cande and Kent (1992). Ocean floor features from Scherwath et al. (2006) and Contreras-Reyes (2008). (B) The Andean Quaternary orogenic front between 36° and 38°S corresponding to the Antiñir-Copahue fault system. Gray area indicates Quaternary deformation superimposed on the Cretaceous to Miocene fold and thrust belt. Ages in rectangles indicate temporal constraints in deformation (see text for further description).

four distinctive fault systems (Figs. 3 and 4). (1) South of 38°30′S, beyond the scope of this study, the intra-arc NNE Liquiñe-Ofqui fault system (Fig. 3) has been described as a dextral strike-slip fault zone from seismic and kinematic points of view (Lavenu and Cembrano, 1999; Rosenau et al., 2006). (2) To the north, between 37°30′ and 38°30′S, this scheme passes into a series of NE- to ENE-trending dextral transtensional faults grouped in the Mandolegüe fault system (Figs. 3 and 4). These faults are associated with pull-apart depocenters diachronously formed between 5 Ma and 2.5 Ma at the arc zone (Melnick et al., 2006b), and between 1.5 and 0.6 Ma at the western retroarc zone, and even younger than 100 ka at the foreland zone (Fig. 3) (Folguera et al., 2004). This fault system tectonically affects a fold and thrust belt active at 97–10 Ma, as determined by fission-track data, intrusive crosscutting relationships, and synorogenic strata (Zamora Valcarce et al., 2009). (3) Between 36° and 37°30′S, a series of N to NW dextral transpressional faults, grouped in the Antiñir-Copahue fault system (Fig. 3), initially accommodated shortening between 1.7 and 1.4 Ma, the ages of pre- and post-contractional volcanic products in the area, respectively (Folguera et al., 2004, 2006). This system still accommodates shortening at the eastern side of the Andes, based on tectonic scarps displacing soils. (4) Immediately to the north, between 36° and 36°30′S, a series of NE-trending fault systems controlled Quaternary retroarc eruptions associated with graben and half-graben structures, such as the Rahue and Molle fault systems that delimit the northern edge of the Antiñir-Copahue fault system (Fig. 3).

LESS THAN 4 MA OLD SHORTENING AT THE COASTAL CORDILLERA BETWEEN 36° AND 40°S

Neotectonic studies show that the Coastal Cordillera has been exhumed inhomogeneously by compressional structures between 36° and 40°S (Fig. 3) (Melnick et al., 2006a). These studies are in accordance with fission-track analyses that identify the 37°–38°S segment corresponding to the Arauco peninsula as being exhumed in the past 3–4 Ma, in contrast to the rest of the coastal zone, that was uplifted in Late Cretaceous times (Glodny et al., 2007). NW- and NE-oriented structures have accommodated contraction in the past 3.6 Ma corresponding to the Isla Santa María and Lanalhue fault systems (Fig. 3), resulting in the tectonic inversion of Early Cretaceous to early Pliocene extensional depocenters (Melnick et al., 2006a). These structures were responsible for the uplift of Isla Santa María above sea level as well as for the anomalous high

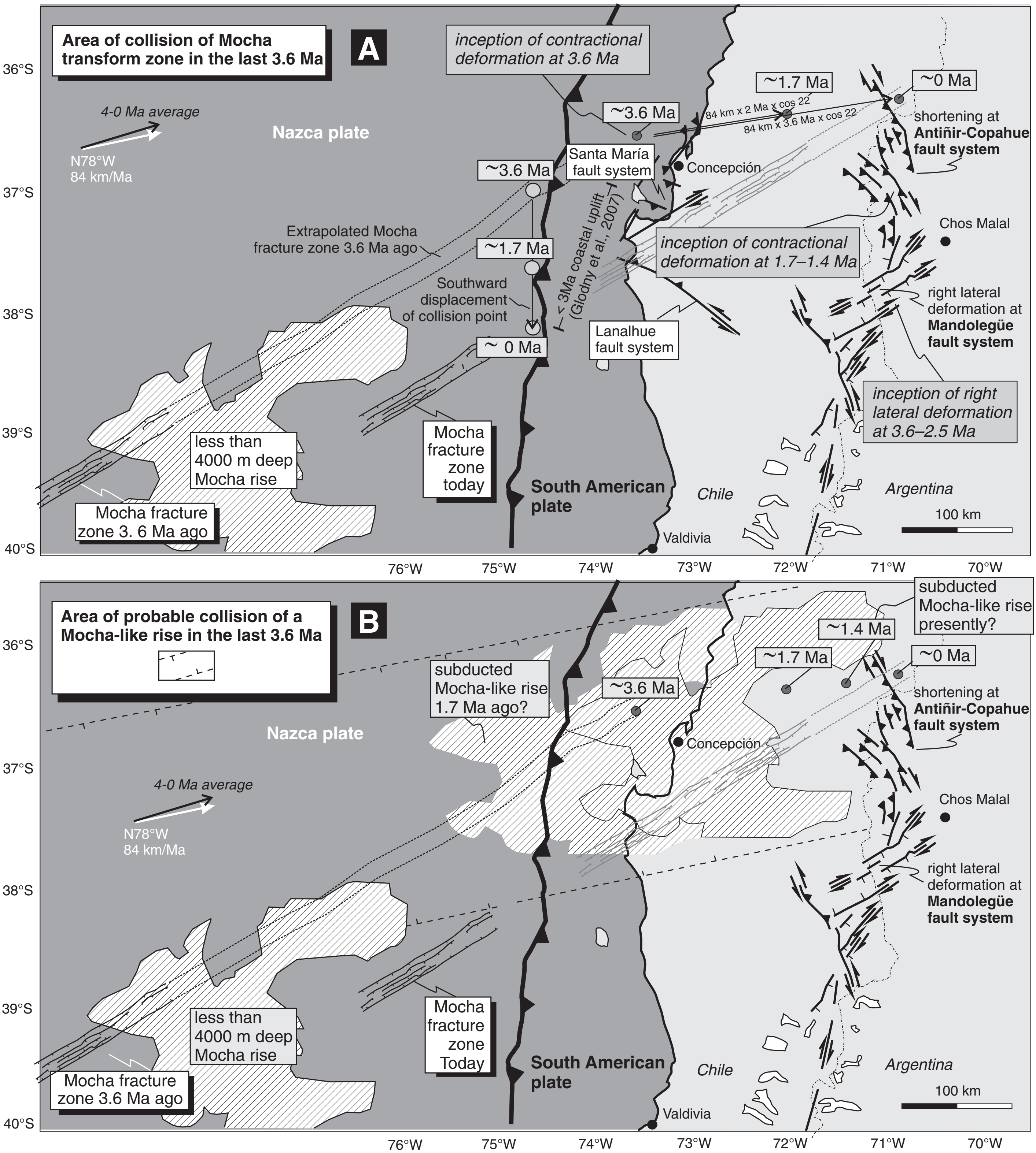

Figure 4. (A) Location of subducted Mocha fracture zone beneath the Andes some 3.6 Ma ago and today, and relation to <3.6 Ma old structure. Eastward progression of contractional deformation since 3.6 Ma in the forearc to 1.7–1.4 Ma in the retroarc zone coincides with the inferred displacement of Mocha fracture zone beneath the South American plate. Note that coastal exhumation determined from fission-track data at <3 Ma (Glodny et al., 2007) coincides with the area corresponding to the Mocha fracture zone interacting with the South American plate, and particularly with the area occupied by the inferred Mocha-like rise. (B) The inferred Mocha-like rise beneath the South American plate has a latitudinal extent compatible with the 200-km-long, out-of-sequence Antiñir-Copahue fault system.

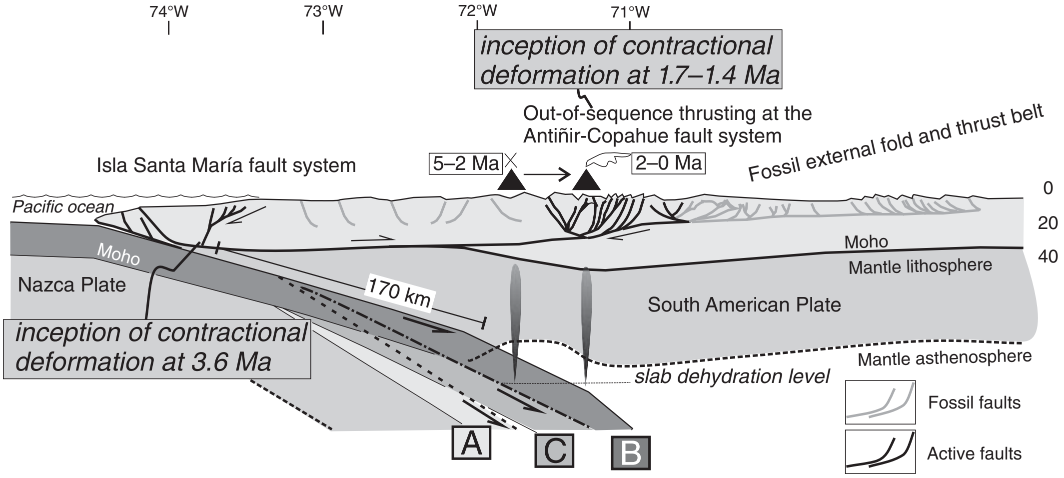

Figure 5. Cross section located at 37°S, neotectonic deformation, and Wadatti-Benioff geometries for three adjacent segments determined from seismic refraction (Krawczyk et al., 2006) (see location in Fig. 2). Black triangles indicate positions of early Pliocene and Quaternary arc fronts, respectively. Retroarc neotectonic structure is from Folguera et al. (2004, 2006), and offshore neotectonic structure is from Melnick et al. (2006a).

relief of the cordillera de Nahuel Buta region between 37° and 38°S (Fig. 3) (Melnick et al., 2006a; Glodny et al., 2007).

COLLISION OF THE MOCHA FRACTURE ZONE WITH THE SOUTH AMERICAN MARGIN

Relative convergence between the Nazca and South American plates in the past 4 Ma inferred from ocean magnetic anomalies (Fig. 3) (Cande and Kent, 1992) implies that 3.6–3 Ma ago, at the time of inception of contractional deformation at the Chilean coast between 37° and 38°S (Melnick et al., 2006a; Glodny et al., 2007), the point of interaction between the Mocha fracture zone and the Chilean trench would have been located some 130 km north of its present position (Figs. 3 and 4). Extrapolating its trend from this 3.6 Ma position at the Chilean trench to the coastal zone, the meridian corresponding to the Lanalhue and Santa María fault systems, where contractional deformations started, would be reached at ~36°30′S (Fig. 4A). Roughly two million years separate inception of contractional deformation at the Chilean coast from younger contractional deformations at the Antiñir-Copahue fault system in the retroarc area (Figs. 3 and 4). Therefore, the Mocha fracture zone and associated Mocha-like rise have been displaced beneath the South American continent some 280 km parallel to relative plate motion (corrected by the cosine of ~22°, corresponding to the Nazca plate subduction angle at the site of its present collision with the Chilean trench) (Fig. 4B). This implies that the point along the fracture zone where the obstacle or asperity that initially produced deformation at the forearc zone is hosted would be located approximately at 36°20′S, beneath the western retroarc area (Fig. 4). That is in accordance with highly hydrated magmas at those latitudes in the Quaternary Nevado de Longaví volcano, interpreted from anomalously high dehydration of the serpentinized Mocha fracture zone at the asthenospheric wedge (Sellés et al., 2004).

DISCUSSION

The Mocha fracture zone has been described as a highly serpentinized zone both from near-shore seismic studies and the nature of arc-related magmas at the place where its trend reaches the arc front. Seismic refraction studies and gravity data show that subduction of the Nazca plate at the site of inferred subduction of a Mocha-like rise since 3.6 Ma ago (~36°30′–37°30′S) is on the order of 6° shallower than in neighboring segments. This zone coincides with the development of <3.6 Ma contractional structures in the Coastal Cordillera and 1.7–1.4 Ma shortening at the arc and western retroarc areas. A 280 km distance separates both areas of young tectonic activity, coinciding accurately with the time necessary to subduct the point along the Mocha fracture zone that initially produced deformation at the forearc area, from beneath the coastal domain to the western retroarc zone. An oceanic "plateau" of similar dimensions to the one surrounding the present Mocha fracture zone could have been subducted beneath the South American plate, justifying the accurate latitudinal extent of this renewed wave of contractional deformations in the Andes. Considering that dehydration of the Nazca plate beneath the South American plate is now produced at the intersection between a vertical plane at the arc front and the Nazca plate itself, we can speculate that this depth has remained unique through recent time for the pressure and temperature conditions to generate arc magmas (Fig. 5). Subducted slab geometry at the latitudes of shallowing (B in Fig. 2) could be used for determination of the dehydration depth at ~37°S as depicted in Figure 5. The line of intersection of this horizontal plane (magma production depth at ~37°S) with a slab of geometry determined beyond the area of subduction of the Mocha fracture zone in the past 3.6 Ma (C in Fig. 2; ~38°S) occurs just beneath the early Pliocene arc front (Fig. 5). This implies that shallowing of the Nazca plate at the site of Mocha-like rise subduction (~37°S) would have involved a steeper geometry close to that of its neighboring segments.

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